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HIGH INTENSITY POSITRON BEAM AND ANGULAR CORRELATION EXPERIMENTS AT LIVERMORE*

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A positron beam apparatus that produces a variable energy positron beam with sufficient intensity to perform new positron experiments in an ultrahigh vacuum environment has been installed at the Lawrence Livermore 100 MeV electron linac. We have installed two large area position sensitive gamma-ray detectors to measure angular correlations in two dimensions and a separate highly collimated detector to measure positronium energy distributions by time-of-flight velocity determination. Data from measurements on single crystals of Cu will be described.

INTRODUCTION

Since the successful demonstration that an intense, low-energy beam of positrons could be produced from the electron beam at the Lawrence Livermore 100 MeV electron linac (1) we have installed an apparatus that allows us to perform experiments with the positron beam in a low radiation background, ultrahigh vacuum environment (2). The positron beam can be varied in energy from 0.5 to 20 keV and is produced in pulses with 0.010 to 3 microseconds duration, with as many as 10^6 positrons per pulse. The ultrahigh vacuum chamber has a base pressure of 2×10^{-10} torr and is equipped to sputter clean, Auger analyze, and heat the samples contained within.

We have performed measurements of the electron-positron momentum distribution for positrons trapped at the surface of a sample and of positronium decaying in flight by measuring the annihilation radiation angular correlation in two dimensions, 2D-ACAR. We have also measured the energy distribution of Ps ejected from the surface of clean copper samples by measuring the time-of-flight of Ps decaying in front of a well collimated detector, Ps-TOF, and measured the amount of Ps produced from the time spectrum of all annihilation gamma rays.

ACAR MEASUREMENTS

Our 2D-ACAR distributions were measured with a system developed along lines similar to West's using position sensitive Anger camera gamma-ray detectors each consisting of a 13 mm by 400 mm NaI crystal connected to an array of 37 phototubes (3). The position resolution of a single camera was 8 mm so that with the detectors at 13.67 m we had an angular resolution of 0.9 mrad. Valid gamma-ray events were selected by requiring a coincidence between the two Anger camera detectors and the pulse of positrons from the linac. Positions and relative detection time for each event were stored on tape and the angular correlation distributions were calculated and corrected by the geometric efficiency matrix after the experiment.

The positron beam was produced in 3 microsecond wide pulses at 900 per second. Only 5% of the available positron intensity was used due to detector saturation. Even so, the high intensity of the positrons in the beam pulse resulted in accidental backgrounds and loss of events due to pileup rejection larger than those in systems using random positron sources. Pile-up events were rejected by taking the first event in the energy window of each detector for each beam pulse. Accidental coincidences were minimized during the analysis of the data by setting a narrow time window on the valid events. Events that satisfied all constraints but were outside the time window were made into accidental angular correlation spectra that were then normalized and subtracted from the data as background.

The sample in these measurements (4) was a single crystal of copper oriented with the [121] axis along the beam direction and the [111] axis along the line joining the camera centers. The surface was cleaned by Argon sputtering and there was less than 10% surface contamination at the end of a 24 hr run.

Perspective drawings of the smoothed 2D-ACAR spectra obtained with 18 keV and 740 eV positrons are shown in Fig. 1. The positron beam is moving in the positive p_z direction as it strikes the surface. For 740 eV the sample was biased to attract re-emitted positrons; for 18 keV it was set at zero to enhance the bulk nature of the data. The background from accidental coincidences that was subtracted from both angular distributions is shown below the 740 eV spectrum. Approximately 5×10^5 counts are shown in each of these spectra, representing ~24 h of data collection.

The data accumulated at 18 keV are similar to those reported by Berko and co-workers (4) for positrons annihilating in the bulk of an annealed Cu single crystal. In comparison, the 740 eV spectrum is much narrower overall, with an asymmetric shift toward the negative p_z direction due to the annihilation in flight of energetic Ps. Careful inspection of the 18 keV spectrum also reveals a small asymmetric Ps peak which masks the neck usually evident at zero momentum in this crystal orientation. The energetic Ps component was stripped from the underlying spectrum by subtracting the spectrum for positive p_z from that for negative p_z. This procedure has the effect of clamping the asymmetric distribution to zero at zero momentum but only introduces significant error within 0.5 mrad of zero. The maximum energy of the Ps is equal to the value of the negative Ps work function. Taking into account the 0.9 mrad resolution, the maximum Ps momentum is 4.5 +/- 0.25×10^{-3} mc corresponding to a work function energy of -2.6 +/- 0.15 eV in reasonable agreement with the value of -2.4 eV (5) obtained from electron and positron work function values. The most probable Ps momentum is found at $p_z = 2.5 \times 10^{-3}$, $p_y = 0.0$ mc, corresponding to a forward energy of 0.80 eV. In the time-of-flight experiment described below the maximum Ps energy was found to be 2.6 +/- 0.3 eV in reasonable agreement with the present 2D-ACAR results. The yield of energetic Ps in the 740 eV spectra was 4% of the total counts for para-Ps implying 14% total Ps if a statistical distribution of spins is assumed.

The Ps momentum distribution can be calculated using conservation of energy and momentum if the electron energy distribution and electron wave function in the metal are known (7). The contours from this model assuming no momentum dependence in the Ps formation interaction and a free electron distribution for the electrons are compared to the Ps data in the top of Fig. 2. The forward shapes of the contours in the data are qualitatively described by the model. However, significant deviations from the model contours occur for the position of the most probable momentum which is less in the data than in the model, indicating that the simple assumptions used in deriving the model contours may be inadequate.

Because the Ps momentum is strongly shifted toward the vacuum, the distribution of momenta into the sample is nearly Ps free. These data are shown with equally spaced contours for both energies in the bottom frame of Fig. 2.

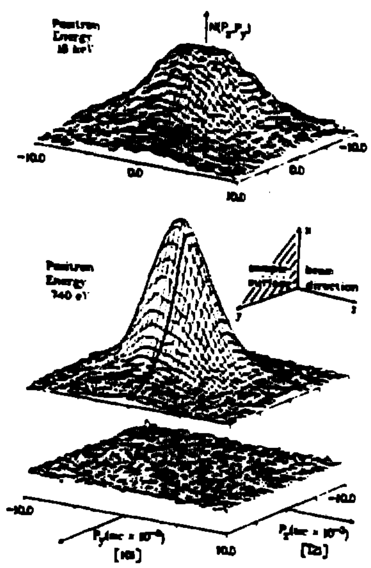

Fig. 1. The 2D-ACAR distribution and background for positron beams of 18 keV and 740 eV impinging on a single crystal of copper. The heavy contour at $p_z = 0$ emphasizes the asymmetry of the low energy data.

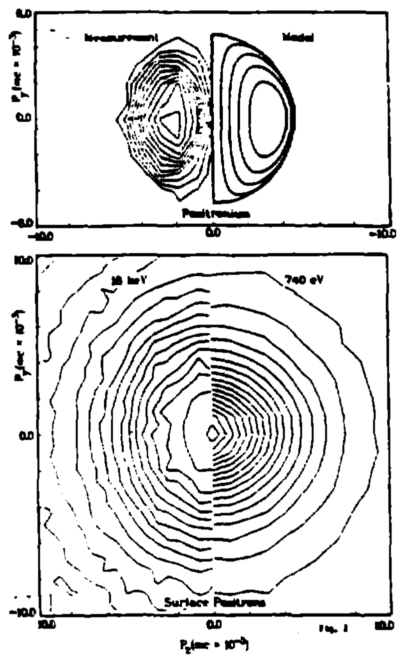

Fig. 2. Top- Contour maps comparing measured and computed momentum distributions for positronium ejected from the copper surface.

Bottom- The positive p_z contours for the 18 keV and 740 eV beams with no energetic positronium contribution.

The narrowing of the pair-momentum distribution of positrons in the surface state compared to the bulk can be seen to be the result of a loss of strength of high momentum components from core electrons and a narrowing of the peak in the low momentum part of the distribution from the valence band. A similar narrowing of 1D-ACAR data for positrons trapped in vacancies and vacancy clusters has been observed (7).

The width of the underlying momentum distribution from the 740 eV data is anisotropic with p_y narrower than p_z (6.6 +/- 0.2 mrad versus 8.0 +/- 0.2 mrad full width at half maximum). Such anisotropy was predicted in the momentum distribution calculated using an independent particle model with a positron trapped in the surface image charge potential of aluminum (8). There is also a strong inferred possibility from the low amount of free Ps found that a localized or trapped Ps contribution may be contained in the broad part of the distribution. In the direction parallel to the surface, delocalization would lead to a narrowing of the momentum distribution so that either picture is consistent with our data.

Ps-TOF MEASUREMENTS

A technique that taks advantage of the pulsed positron beam is time of flight measurements of the Ps velocity. We use a highly collimated detector geometry similar to that reported by Mills (10) to detect Ps decaying in flight at a fixed distance from the Cu surface. Fig. 3 shows data, corrected by the triplet lifetime for decay in flight, obtained with a Ps flight path of 11.5 +/- .5 cm and 15 ns time resolution on the same sample as the 2D-ACAR experiment. These spectra were each obtained in 30 min. The shape of the low temperature distribution is determined by the electron energy distribution at the surface and other factors in the electron- positron interaction along with the measurement geometry and scattered Ps intensity. The low energy Ps resulting from thermal desorption is clearly seen as an additional component in the high temperature data in Fig. 3. From these data we can derive the Ps workfunction energy quoted above, accurate distributions for the thermally desorbed Ps and eventually the surface electron energy distribution.

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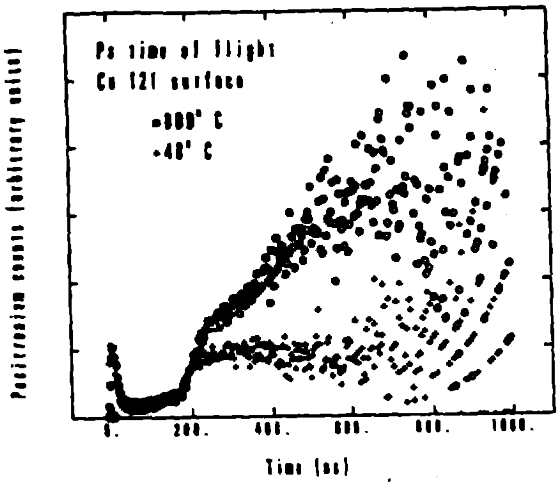

Fig. 3. Positronium time-of-flight distributions for clean copper at room temperature and 800°C.

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